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Using EPIC model to manage irrigated cotton and maize

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ABSTRACT

Simulation models are becoming of interest as a decision support system for management and assessment of crop water use and of crop production. The Environmental Policy Integrated Climate (EPIC) model was used to evaluate its application as a decision support tool for irrigation management of cotton and maize under South Texas conditions. Simulation of the model was performed to determine crop yield, crop water use, and the relationships between the yield and crop water use parameters such as crop evapotranspiration (ETc) and water use efficiency (WUE). We measured actual ETc using a weighing lysimeter and crop yields by field sampling, and then calibrated the model. The measured variables were compared with simulated variables using EPIC. Simulated ETc agreed with the lysimeter, in general, but some simulated ETc were biased compared with measured ETc. EPIC also simulated the variability in crop yields at different irrigation regimes. Furthermore, EPIC was used to simulate yield responses at various irrigation regimes with farm fields' data. Maize required ~700 mm of water input and ~650 mm of ETc to achieve a maximum yield of 8.5 Mg ha^{-1} while cotton required between 700 and 900 mm of water input and between 650 and 750 mm of ETc to achieve a maximum yield of 2.0–2.5 Mg ha^{-1}. The simulation results demonstrate that the EPIC model can be used as a decision support tool for the crops under full and deficit irrigation conditions in South Texas. EPIC appears to be effective in making long-term and pre-season decisions for irrigation management of crops, while reference ET and phenologically based crop coefficients can be used for in-season irrigation management.

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1. Introduction

A solution to water shortages for plants is irrigation, which has made agriculture possible in many nonproductive areas (Kramer and Boyer, 1995). In the Wintergarden area of Texas, irrigation is also one of the major limiting factors in producing maize (*Zea mays*), cotton (*Gossypium hirsutum*), and other crops, as more than 90% of the water for urban and agricultural use in this region depends on the Edwards aquifer. As the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 6100 m^3 ha^{-1} of water per year in the Edward aquifer region, maximization of agricultural production efficiency has become a high priority for numerous studies in the Wintergarden area of Texas. For efficient water use, the irrigation amount should not exceed the maximum amount that can be used by plants through evapotranspiration (ET), which is the sum of the amount of water returned to the atmosphere through the processes of evaporation and transpiration (Hansen et al., 1980).

Studies demonstrate that crop simulation models can be used to determine irrigation requirements at farm, county, and state levels (Alexandrov and Hoogenboom, 1999; Guerra et al., 2002, 2005, 2007; Hoogenboom et al., 1991; Heinemann et al., 2002; Liu et al., 2007). Other studies report that crop models can be employed to optimize the allocation of irrigation water during the growing season and among crops (Bryant et al., 1992, 1993; Cabelguenne et al., 1995, 1997; Minacapilli et al., 2008) as well as to evaluate efficient irrigation scheduling strategies (Epperson et al., 1993; Fortson et al., 1989; Santos et al., 2000; Swaney et al., 1983). In South Texas, interest is growing in applying simulation models to better assess crop water use and production with different crop management practices. One of these simulation models is EPIC, which was developed to determine the relationship between soil erosion and soil productivity in the US (Williams et al., 1984). EPIC includes physiologically based components to simulate erosion, growth of multiple crops, soil and plant water, nitrogen and phosphorus balances, and crop and soil management.

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The stress factors able to restrain potential crop growth include water, nitrogen, temperature, and aeration. Crop yield is simulated using the harvest index concept, i.e., economic yield divided by aboveground biomass. Model components contain weather, hydrology, erosion, nutrient cycling, soil temperature, crop growth, tillage, pesticide fate, economics, and plant environmental control. The EPIC hydrology component includes runoff, percolation, lateral subsurface flow, ET, and snow melt. EPIC comes with five ET equations from which the user has to make a single choice for a simulation exercise. The equations are as follows: Penman (Penman, 1948), Penman–Monteith (Monteith, 1965), Priestley–Taylor (Priestley and Taylor, 1972), Hargreaves–Samani (Hargreaves and Samani, 1985), and Baier–Robertson (Baier and Robertson, 1965).

The generic crop growth subroutine in EPIC (Williams et al., 1989) facilitates the simulation of complex rotations and fallow-cropping systems, making the model useful for evaluating alternative crop management scenarios in South Texas. A variety of scenarios can be simulated with the model, such as evaluating crop water use. A critical step in constructing crop management scenarios with EPIC is to validate the model in the region of interest. The objective of this research was to calibrate and apply EPIC to irrigation management of cotton and maize in South Texas. The model was used in simulating crop yield and crop water use parameters such as crop evapotranspiration and water use efficiency. We also determined crop water use, and the relationships between the yield and the parameters.

2. Materials and methods

2.1. Data for validation of EPIC

Field studies for validation of the EPIC model were conducted at the Texas AgriLife Research Center in Uvalde, Texas (N29°13′03″, W99°45′26″, elevation 283 m), in 2002, 2003, 2004, 2005, and 2006. Maize and cotton were grown in two similarly managed fields, one from a center-pivot-irrigated field with a low energy precision application (LEPA) system and the other from a linear-irrigated lysimeter field with a LEPA system. Cultivars and plant to maturity dates in each year are presented in Table 1. Soil type of both fields was an Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1). The experimental design under the center pivot (20 ha) was arranged in a split–split design with irrigation treatments, cultivar sub-treatments with three blocks (Fig. 1). A 90° wedge of the center-pivot-circled field was divided equally into 15° regimes, which were maintained at 100, 75, and 50% crop evapotranspiration (ETc) values. The lysimeter units used in this study had monolithic soil cores where soil structure and associated parameters remain unchanged (Marek et al., 2006). Each lysimeter (1.5 m × 2.0 m × 2.1 m) is placed in the middle of a 1-ha field. The lysimeter field was managed under full irrigation based on measured daily crop water use. For the pivot experiment, irrigation scheduling and ET regimes for the field were imposed according to daily calculations of the FAO Penman–Monteith equation (Allen et al., 1998). Actual crop water use requirements for cotton were determined based on the relation to a well-watered reference grass. The equation was as follows:

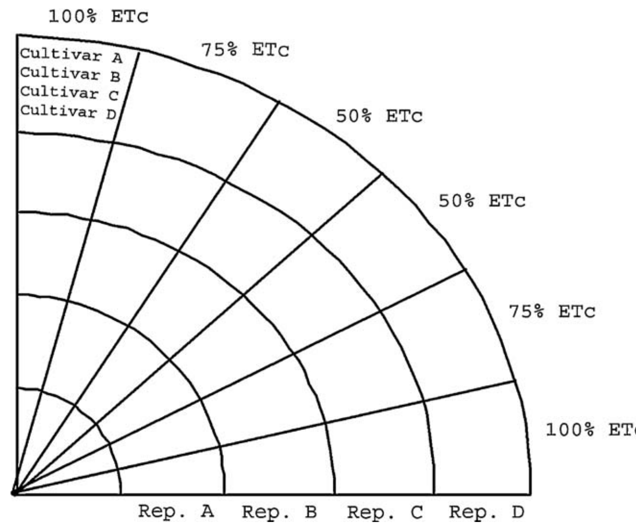

Fig. 1. Field map of the experiment of the center-pivot field at Texas A&M AgriLife Research Center in Uvalde, Texas.

$$ETc = Kc \times ETo \quad (1)$$

where Kc is crop coefficient and ETo is reference evapotranspiration. ET from a tall fescue grass (*Festuca arundinacea* Schreb.) with a height of 0.12 m and a surface resistance of 70 s m^{-1} was the ETo surface employed in Kc. The total amounts of irrigation and rainfall during the crop season for each year are presented in Table 1. The years of 2006 and 2007 were recorded as the extremely dry and wet years, respectively, during the last 20 years in South Texas.

The plant growth model in EPIC simulates agronomic crops, pastures, and trees, with each crop having unique values for the model parameters (Table 2). The biomass to energy ratio (WA) is the crop parameter for converting solar energy into biomass. The harvest index (HI) is the ratio of economic yield to the aboveground biomass. The potential heat unit (PHU) is the number of heat units expected for a typical growing season (from planting date to harvest date) for the crop to mature. Heat units are

Table 1
Summary of cropping practices at the Texas AgriLife Research Center in Uvalde, Texas.

Crop	Variety[a]	Year	Plant-maturity (M/D)	Irrigation (mm)[b]		Rainfall (mm)
				Lysimeter	FAO P–M	
Maize	30G54	2002	3/25-6/20	358.1	422.4	99.6
	30G54	2003	3/18-6/24	370.8	417.8	136.7
	30G54	2004	3/10-6/24	293.6	231.1	232.4
Cotton	ST4892	2003	4/02-8/11	N/A	253.5	318.3
	ST4892	2004	4/01-8/16	N/A	257.6	274.1
	ST4892	2005	4/07-8/07	N/A	337.3	140.7
	DP555	2006	4/13-8/20	604.3	N/A	71.3
	DP555	2007	4/16-9/07	76.2	N/A	575.8

[a] 30G54 from Pioneer (Johnston, IA); ST4892 from Stoneville (Monsanto, St. Louis, MO); and DP555 from Delta and Pine (Scott, MS).
[b] Total amounts of irrigation based on crop evapotranspiration using lysimeter-measured and FAO Penman–Monteith (P–M) equation; maize were grown in two similarly managed fields (a linear-irrigated lysimeter field and a center-pivot-irrigated field both using a LEPA system).

Table 2
Yield-related EPIC parameters used for maize and cotton in this study.

Parameter	Symbol[a]	Maize	Cotton
Radiation use efficiency (kg ha^{-1} MJ m^{2})	WA	43	25
Harvest index	HI	0.55	0.45
Potential heat unit (°C)	PHU	1200–2400	1200–2400
Water stress-harvest index coefficient	PARM (3)	0.5	0.5
SCS curve number index coefficient	PARM (42)	1.0	1.0
Difference of soil water contents at field capacity and wilting point (mm^{-1})	DIFFW	0.2	0.2

[a] Parameter symbols used in the EPIC model.

accumulated degrees of temperature (°C) between the day's mean temperature and the crop's minimum growth temperature. The water stress-harvest index, PARM (3), sets the fraction of growing season when water stress starts to reduce the HI. The SCS curve number index coefficient, PARM (42), regulates the effect of potential evapotranspiration in driving the SCS curve number retention parameter. The retention parameter impacts runoff volume and changes with soil water content. The differences of soil water contents for each layer between field capacity and wilting point (DIFFW) impact water storage for plant use and water stress factor for crop growth.

Variables for the model validation were ETc and crop yield. We determined daily crop water use using lysimeter-measured and two different calculation methods (FAO Penman–Monteith-based and EPIC-simulated ETc), which were determined under unstressed crop conditions. FAO Penman–Monteith ETo method in conjunction with crop coefficients developed at Bushland, TX (2002–2003), and Uvalde, TX (2004), were used to calculate FAO Penman–Monteith-based ETc. The EPIC model requires users select one ET equation from the five options that were listed in the previous section. After preliminary test runs of the EPIC model, the Hargreaves–Samani (Hargreaves and Samani, 1985) ETo method was selected to simulate ETc in this study. In addition, lysimeter-measured crop water use under unstressed crop conditions was previously compared to two different methods of estimating ETc: (1) calculation using FAO Penman–Monteith formula and (2) EPIC simulated using Hargreaves–Samani (Piccinni et al., 2005). No statistical difference was found between the seasonal total ETc from lysimeter measurement and those estimated with the two methods. This was performed as a preliminary validation of the EPIC model.

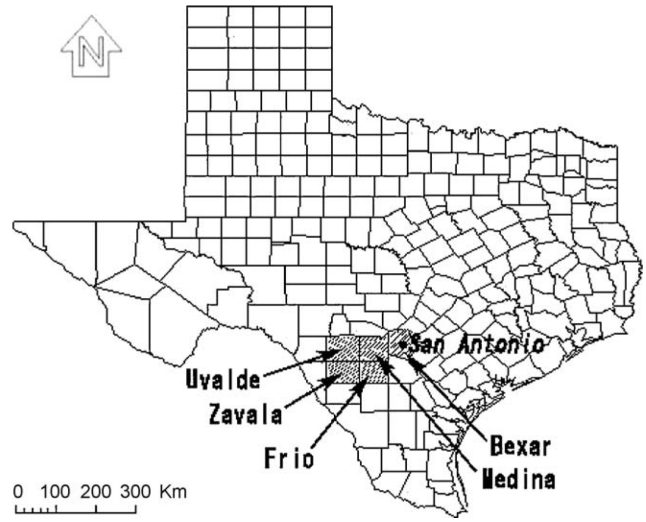

Fig. 2. Map of the region where maize and cotton data were obtained for parameterization and simulation.

2.2. Crop simulation of farm fields

The EPIC model was applied to simulate on-farm crop yield of cotton and maize in South Texas in 2006 and 2007 (Fig. 2). Information regarding the farms and their cropping practices is presented in Table 3. Six farm fields were operated for the simulation study for each crop and each year. The model was then used to simulate the yield of each crop with various irrigation

Table 3A
Summarized information of farms and their cropping practices in 2006 used in crop simulation.

Crop	Site	County	Latitude (N), longitude (W); elevation (m)	Soil type	Plant to harvest (M/D)	N–P[a] (kg ha^{-1})	Irrigation (mm)
Maize	1	Medina	29.397, 98.893; 252	Knippa clay 0–1%	3/11-7/22	163–19	622
	2[b]	Medina	29.335, 99.365; 315	Montell clay 0–1%	3/03-8/01	101–90	427
	3	Uvalde	29.176, 99.760; 268	Uvalde silty clay loam 0–1%	3/03-7/30	168–56	610
	4	Uvalde	29.255, 99.764; 303	Uvalde silty clay loam 0–1%	3/08-8/10	168–45	495
	5	Bexar	29.359, 98.723; 192	Brayton clay 0–1%	3/10-8/26	163–46	533
Cotton	6	Zavala	28.902, 99.568; 201	Uvalde silty clay loam 0–1%	4/10-8/29	103–0	425
	7[b]	Uvalde	29.191, 99.855; 282	Montell clay 0–1%	3/30-8/29	56–0	406
	8	Uvalde	29.293, 99.762; 302	Knippa clay 0–1%	4/04-8/29	50–129	464
	9	Uvalde	29.284, 99.761; 297	Knippa clay 0–1%	3/21-8/29	123–45	419
	10	Frio	28.898, 99.126; 181	Duval loamy fine sand 0–5%	4/05-9/02	123–0	533

[a] Nitrogen–phosphate applied.
[b] Two fields were used from these sites.

Table 3B
Summarized information of farms and their cropping practices in 2007 used in crop simulation.

Crop	Site	County	Latitude (N), longitude (W); elevation (m)	Soil type	plant to harvest (M/D)	N–P[a] (kg ha^{-1})	Irrigation (mm)
Maize	1	Uvalde	29.191, 99.855; 282	Montell clay 0–1%	2/24-8/15	111–67	152
	2	Uvalde	29.293, 99.762; 302	Knippa clay 0–1%	3/07-7/21	120–90	150
	3	Medina	29.265, 99.486; 267	Knippa clay 0–1%	3/10-8/21	124–55	152
	4	Uvalde	29.271, 99.687; 282	Knippa clay 0–1%	3/10-8/21	124–55	51
	5	Uvalde	29.284, 99.761; 297	Knippa clay 0–1%	3/15-7/10	150–80	127
	6	Bexar	29.313, 98.650; 300	Lewisville silty clay 0–1%	3/10-8/14	117–75	0
Cotton	7	Medina	29.375, 98.971; 309	Victoria clay 0–1%	4/05-10/15	94–47	0
	8	Medina	29.397, 98.893; 251	Knippa clay 0–1%	4/10-9/28	183–66	0
	9	Medina	29.320, 99.368; 334	Montell clay 0–1%	4/20-9/10	100–0	25
	10	Uvalde	29.176, 99.760; 268	Uvalde silty clay loam 0–1%	4/04-8/20	110–60	0
	11	Medina	29.335, 98.798; 213	Lewisville silty clay 0–1%	4/26-10/23	120–40	76
	12	Bexar	29.333, 98.626; 208	Houston Black gravelly clay 0–1%	4/17-10/01	140–105	0

[a] Nitrogen–phosphate applied.

scenarios for the farm fields. The typical irrigation scenarios were 229, 306, 381, 457, 533, and 610 mm, respectively. Irrigation regimes for simulation to the farm fields were applied based on the actual irrigation management regime for each field. Simulation modeling was performed using 20-year climate data (i.e., from 1987 to 2006 for the simulation of the year 2006 and from 1988 to 2007 for the simulation of the year 2007). Since simulation responses showed somewhat different for the both years due to the extreme differences in precipitation (71 mm in 2006 and 576 mm in 2007), we present the simulation results of the both years. The results of the years 2006 and 2007 are classified into dry year-based irrigation management (DYIM) and wet year-based irrigation management (WYIM), respectively. In data presentation, simulation results of two extreme (dry and wet) years from each 20-year simulation were selected to explore crop yield responses to water (i.e., ETc and water input) as well as relationships between water use efficiency (WUE) and crop yield, and WUE and water. For the DYIM regime, the years 2006 and 1987 were used as typical dry and wet years, respectively. For the WYIM regime, the years 2006 and 2007 were used as distinctive dry and wet years, respectively.

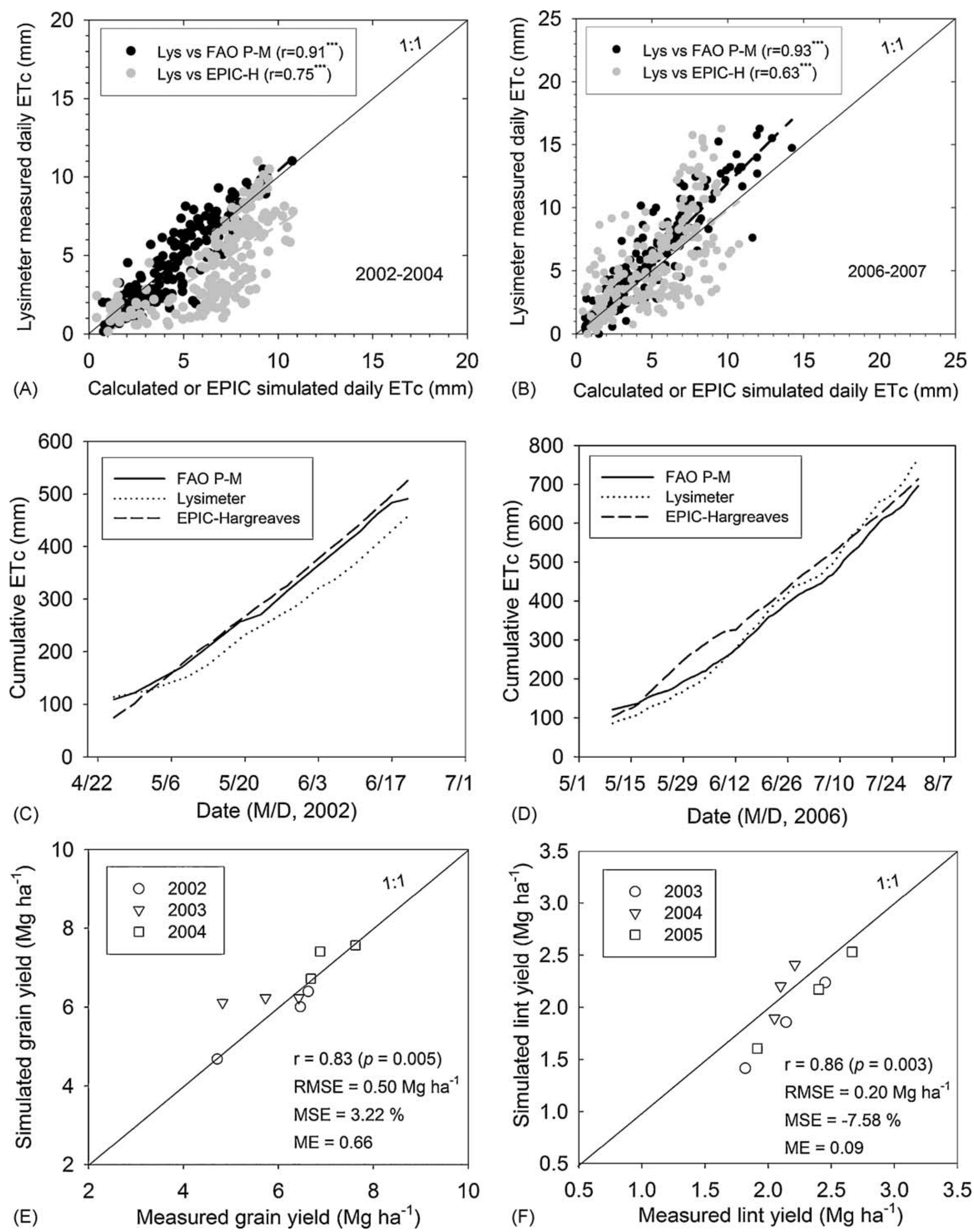

Fig. 3. Lysimeter-measured daily crop evapotranspiration, ETc, versus two methods of estimating ETc (calculation using FAO Penman–Monteith equation and EPIC-simulated using Hargreaves–Samani) for maize (A) and cotton (B); cumulative ETc values (corresponding to A and B) as a function of date for maize (C) and cotton (D); and measured versus simulated yield of maize (E) and cotton (F) at the Texas A&M AgriLife Research Center in Uvalde, Texas.

In this study, water use efficiency (WUE) is defined with the following two equations:

$$\mathrm{WUE}_{\mathrm{ETc}} = \frac{\mathrm{Y}}{\mathrm{ETc}} \tag{2}$$

where $\mathrm{WUE}_{\mathrm{ETc}}$ ($\mathrm{g\,m^{-2}\,mm^{-1}}$) is water use efficiency calculated with seasonal crop water use in terms of crop evapotranspiration (ETc in mm) and Y ($\mathrm{g\,m^{-2}}$) is the crop yield.

$$\mathrm{WUE}_{\mathrm{I+R}} = \frac{\mathrm{Y}}{\mathrm{I+R}} \tag{3}$$

where $\mathrm{WUE}_{\mathrm{I+R}}$ ($\mathrm{g\,m^{-2}\,mm^{-1}}$) is water use efficiency calculated with seasonal water input (mm), or irrigation (I) + rainfall (r).

Weather data used in the simulations were collected with a standard automatic Campbell Scientific meteorological station (Campbell Scientific Inc., Logan, UT) at each location. Correlation analysis using PROC CORR and paired t-test using PROC TTEST (SAS version 9.2, Cary, NC) were used to compare yields of simulated and measured data. Goodness-of-fit estimators used were p value from the paired t-test and correlation coefficient (r). To evaluate the model performance, four statistics are also used: (i) root mean square error (RMSE), Eq. (4); (ii) mean relative error (MRE), Eq. (5) and (iii) model efficiency (ME), Eq. (6):

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{n}(S_i - M_i)^2\right]^{1/2} \tag{4}$$

$$\mathrm{MRE}\,(\%) = \frac{1}{n}\sum_{i=1}^{n}\frac{S_i - M_i}{M_i} \times 100 \tag{5}$$

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - M_a)^2} \tag{6}$$

where S_i is the ith simulated value, M_i is the ith measured value, M_{avg} is the averaged measured value, and n is the number of data pairs. ME values are equivalent to the coefficient of determination (R^2), if the values fall around a 1:1 line of simulated versus measured data, but ME is generally lower than R^2 when the predictions are biased, and can be negative.

3. Results

3.1. Model calibration on maize and cotton

While no statistical difference was found between the seasonal total ETc values of lysimeter-measured and the two different methods of irrigation calculation (Piccinni et al., 2005), daily and cumulative ETc values varied during the growing season among the three methods of measurements (Fig. 3A–D). In-season differences among ETc methods varied possibly due to inexact simulation growth curves or growth stage specific crop coefficients; however, the variations were within an acceptable range (r = 0.75 and 0.65 for maize and cotton, respectively).

The EPIC model simulated the variability in maize grain yield with different irrigation regimes in the experimental set-up, with

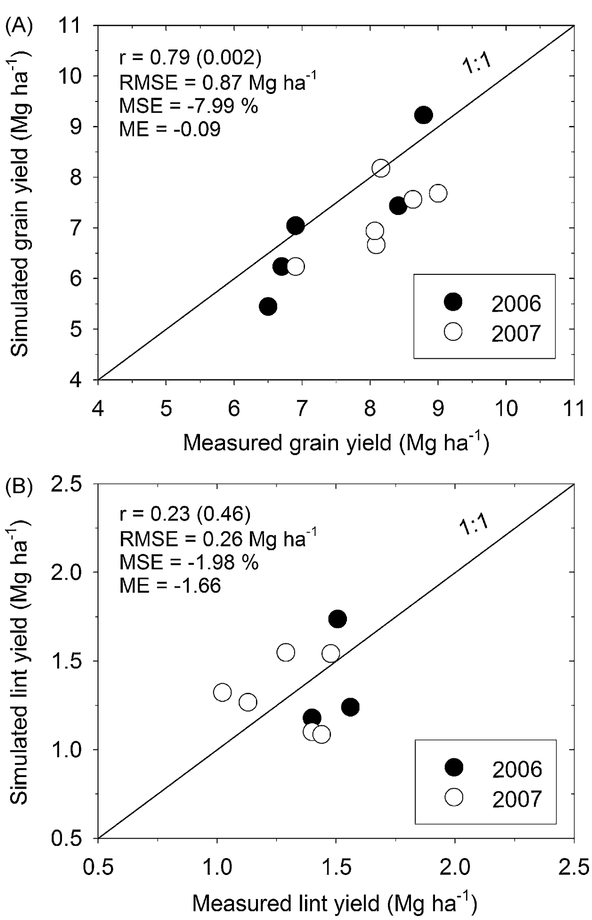

Fig. 4. Measured versus simulated grain yield of maize (A) and measured versus simulated lint yield of cotton (B) using farm field data, which were obtained from five South Texas counties (Bexar, Frio, Medina, Uvalde, and Zavala) in 2006 and 2007.

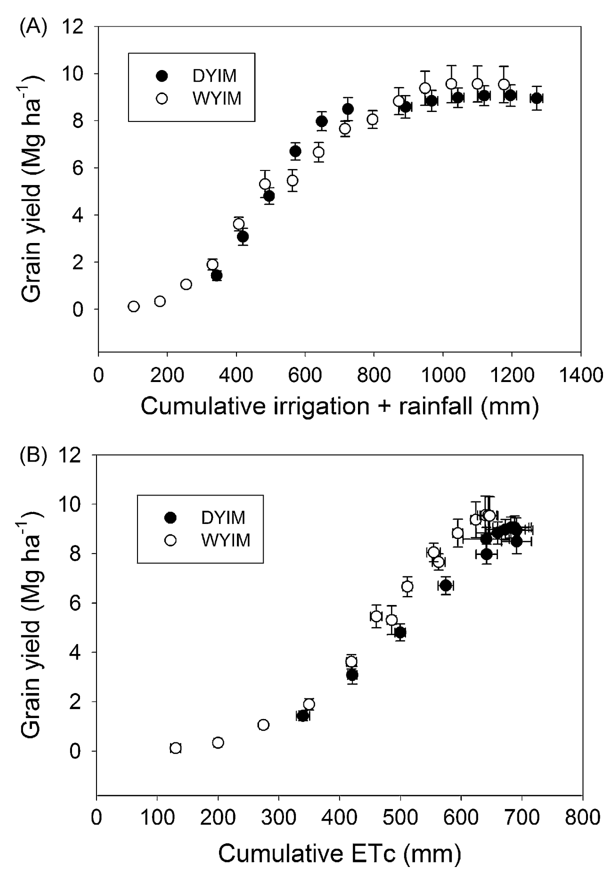

Fig. 5. Maize yield responses as a function of cumulative irrigation + rainfall (A) and crop evapotranspiration, ETc, (B) simulated with dry year-based irrigation management (DYIM) and wet year-based irrigation management (WYIM). Data were normalized using the yield responses of the two extreme (dry and wet) years from each of 20-year (1987–2006 and 1988–2007) simulations for six farm fields. Vertical bars represent errors at 95% confidence interval for the mean of each data point.

an r value of 0.83, root mean square error (RMSE) of 0.50 Mg ha^{-1}, mean relative error (MRE) of 3.2%, and model efficiency (ME) of 0.66 (Fig. 3E). Paired t-test showed that simulated yield was not significantly different from the measured yield with $p = 0.41$. For the 3 years, measured yield ranged from 4.71 to 7.62 Mg ha^{-1} while simulated yield ranged from 4.68 to 7.56 Mg ha^{-1}. For cotton, EPIC simulated the variability in lint yields, with an r value of 0.86, RMSE of 0.70 Mg ha^{-1}, MRE of −7.58%, and ME of 0.09 (Fig. 3F). Simulated yield was in agreement with the measured yield according to paired t-test ($p = 0.06$). For the 3 years, measured yield ranged from 1.82 to 2.67 Mg ha^{-1} while simulated yield ranged from 1.35 to 2.46 Mg ha^{-1}. Previously, Williams et al. (1989) reported that EPIC could accurately simulate crop responses to irrigation at locations in the western USA. Here, our calibration results demonstrate that the EPIC model can be used as a decision support tool for irrigation management of maize and cotton in South Texas environment.

3.2. Crop simulation for farm fields

Measured grain yield of maize ranged from 6.50 to 9.00 Mg ha^{-1} while simulated grain yield ranged from 5.45 to 9.23 Mg ha^{-1} (Fig. 4A). Simulated grain yield was in agreement with measured grain yield with r value of 0.79, RMSE of 0.87 Mg ha^{-1}, MRE of −7.99%, and ME of −0.09. Simulated maize grain yield was statistically in disagreement with the measured yield ($p = 0.01$). Meanwhile, measured lint yield of cotton ranged from 1.40 to 1.61 Mg ha^{-1} while simulated lint yield ranged from 1.18 to 1.74 Mg ha^{-1} (Fig. 4B). Simulated lint yield matched with measured lint yield with r value of 0.23, RMSE of 0.26 Mg ha^{-1}, MRE of −1.98%, and ME of −1.66. Paired t-test showed that simulated cotton lint yield was not significantly different from the measured yield ($p = 0.51$). While the model efficiencies were poor for the simulation results of both maize and cotton, the values of RMSE and MRE were relatively small. It is considered that the disagreements can be attributed to biotic or abiotic factors that the current model fails to simulate. Even so, the crop model simulated the variability in grain yield of maize and lint yield of cotton from the different farms at the different irrigation applications with an acceptable precision. Assuming that EPIC reproduced the crop yield variation from the farm fields, the model was applied to simulate yield responses with various irrigation scenarios.

Maize grain yield showed parabola-curve responses to water input (irrigation + rainfall) as well as ETc (Fig. 5). Grain yield as a function of water input increased with an exponential phase up to 400 mm and with a linear phase until 700 mm, reaching a plateau after that. This result allows us to assume that the amount of water necessary to achieve ∼8.5 Mg ha^{-1} for maize is ∼700 mm. Grain yield in relation to ETc increased exponentially up to ∼400 mm and linearly until ∼650 mm, which is considered to be a saturated ETc for maize in this region.

Water use efficiency (WUE) responded to grain yield with either a threshold-like or a parabolic curve depending on the WUE formulas used while WUE responses to water input and ETc showed parabolic curve patterns (Fig. 6). WUE_{I+R} generally reached a plateau at ∼8 Mg ha^{-1} both in the dry and wet years. The result

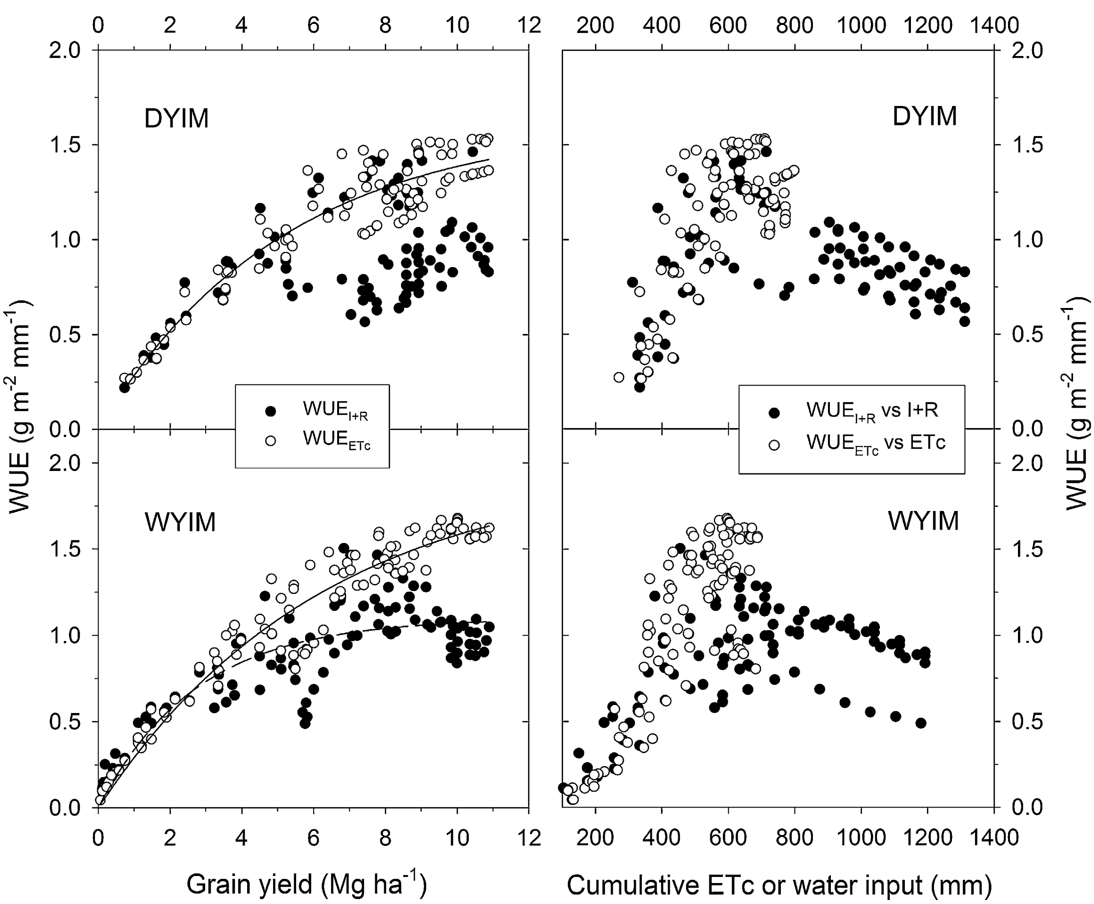

Fig. 6. Water use efficiency, WUE, in relation to maize grain yield, Y, (left) and WUE in relation to cumulative crop evapotranspiration, ETc, and water input or irrigation, I, + rainfall, R, (right), simulated with dry year-based irrigation management (DYIM) and wet year-based irrigation management (WYIM). Data points ($n = 72$) include the two extreme (dry and wet) years from each of 20-year (1987–2006 and 1988–2007) simulations for six farm fields at six different irrigation regimes. $WUE_{I+R} = Y/(I + R)$ and $WUE_{ETc} = Y/ETc$. The fit curve equations are $WUE_{ETc} = 0.16(1 - \exp(-0.19Y))$, $R^2 = 0.88$ for the DYIM and $WUE_{ETc} = 1.99(1 - \exp(-0.16Y))$, $R^2 = 0.95$ and $WUE_{I+R} = 1.10(1 - \exp(-0.37Y))$, $R^2 = 0.76$ for the WYIM.

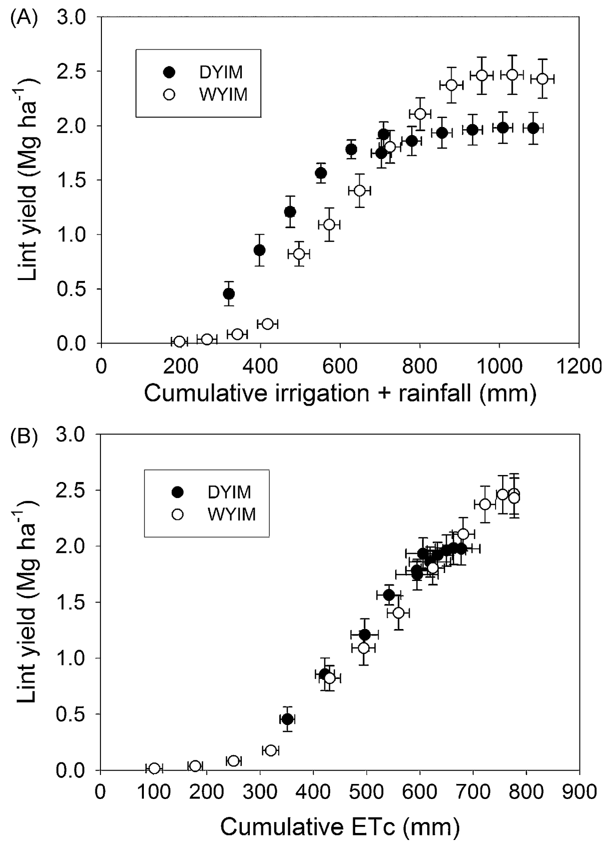

Fig. 7. Cotton lint yield responses as a function of cumulative irrigation + rainfall (A) and crop evapotranspiration, ETc, (B) simulated with year-based irrigation management (DYIM) and wet year-based irrigation management (WYIM). Data were normalized using the yield responses of the two extreme (dry and wet) years from each of 20-year (1987–2006 and 1988–2007) simulations for six farm fields. Vertical bars represent errors at 95% confidence interval for the mean of each data point.

shows that there is a positive correlation between WUE and grain maize yield up to a certain range of yield, which was ~8 Mg ha^{-1}. When the WUE values were plotted against values of ETc and water input, WUE generally increased as ETc or water input increased until ~600 mm. WUE_{I+R} versus water input decreased with a slow linear phase after ~650 mm. Therefore, it is considered that there are positive correlations between WUE_{I+R} versus water input and WUE_{ETc} versus ETc until ~600 mm while there is a negative correlation between WUE_{I+R} and water input after ~650 mm. This value was determined to be the amount of ETc needed to achieve the range of the highest maize grain yield in this study.

Likewise for maize, cotton lint yield responded with parabolic-curve patterns to water input (irrigation + rainfall) and ETc (Fig. 7). However, lint yield responses showed somewhat different between the dry and wet years. Lint yield as a function of water input reached a plateau at ~700 mm in the dry year and at ~900 mm in the wet year. The yield in relation to ETc reached a plateau at ~650 mm in the dry year and at ~750 mm in the wet year. The different responses of lint yield for the different years to water input and ETc are considered being related to either the water application (irrigation + rainfall) schemes for modeling or less possibly the indeterminate habit of cotton (Bourland et al., 2001) or both. Since there were more frequent rainfall events in the wet year (2007), it appears that the water distribution during the crop season of the year 2007 was sensitively affected to the lint yield (i.e., more favorably for the greater amount of water and less favorably for the less amount of water) while it was not the case for maze (see Fig. 4). Based on the present results, we assume that the amount of water necessary to achieve 2.0–2.5 Mg ha^{-1} for cotton is between 700 and 900 mm. The result additionally shows that cotton is saturated between 650 and 750 mm of ETc under the South Texas conditions.

WUE generally showed either threshold-like or parabolic curve responses to lint yield, water input, and ETc (Fig. 8). Likewise for maize, it is considered that there is a positive correlation between WUE and cotton lint yield up to a certain range of lint yield, which was ~1.5 Mg ha^{-1}, showing higher WUE in the dry year. When the WUE values of cotton were plotted against values of ETc and water input, WUE generally increased as ETc or water input increased until ~600 mm in the dry year and until ~700 mm in the wet year. WUE_{I+R} decreased with a slow linear phase after those values. We assume that there are positive correlations between WUE_{I+R} versus water input and WUE_{ETc} versus ETc up to certain ranges of ETc (600 mm in the dry year and 700 mm in the wet year, respectively) while there is a negative correlation between WUE_{I+R} and water input after those values. These values corresponded to the amount of ETc necessary to achieve the range of the highest cotton lint yield.

4. Discussion

The EPIC crop simulation model can be used to assess the impact of weather and management strategies on agricultural production as well as soil and water resources. The model has been used extensively in the US and other counties. Studies reported that EPIC can be one of the recommendable models for simulating long-term average crops (Bryant et al., 1992; Kiniry et al., 1995; Moulin and Beckie, 1993; Touré et al., 1995; Williams et al., 1989). In this study, we used EPIC to evaluate the possibility of using it as a decision support tool for irrigation management of crops under South Texas conditions. The effectiveness of crop simulation models depends on practical accuracy in simulating variables of interest. The calibration results of maize and cotton showed reasonable agreement between simulation and measurement in terms of crop water use and crop yield. However, some reported that the model tended to overestimate low yields (Cabelguenne et al., 1990; Ceotto et al., 1993; Martin et al., 1993; Warner et al., 1997). These studies were performed in a new environment, elsewhere from where it was originally developed. As Kiniry et al. (1995) pointed out, overestimation of the amount of plant-available water at field capacity can cause EPIC to overestimate yield in dry years. They mentioned that it could be helpful to measure maximum depth of water extraction using appropriate cultivars in the region. In addition, appropriate parameter estimation is critical to reproduce the field conditions. It was noted that while most models including EPIC could be well calibrated and effectively applied to many environments, uncertainty about many of the parameters remains, resulting in the overall uncertainty in the simulation results (Wang et al., 2005). Parameterization is a modeling technique that uses an empirical function to approximate the response of a physical system over a given range of environmental conditions (Huschke, 1959). This technique reduces the complexity of models and makes them easier to use for operational purposes. Therefore, efforts with intense investigation of the parameters for EPIC are needed to adequately simulate yield in low and high yielding years.

While EPIC effectively simulates water and nitrogen effects on crop growth, the model fails to biophysically simulate the effects of some of the major biotic and/or abiotic factors on crop growth. These include interactions of nutrients, weed or pest infestations, and field variations of soil chemical and physical properties. We assume that some of the disagreements between simulation and measurement can be attributed to the model constraint on the issues listed. However, a study in detail was not made as it was not

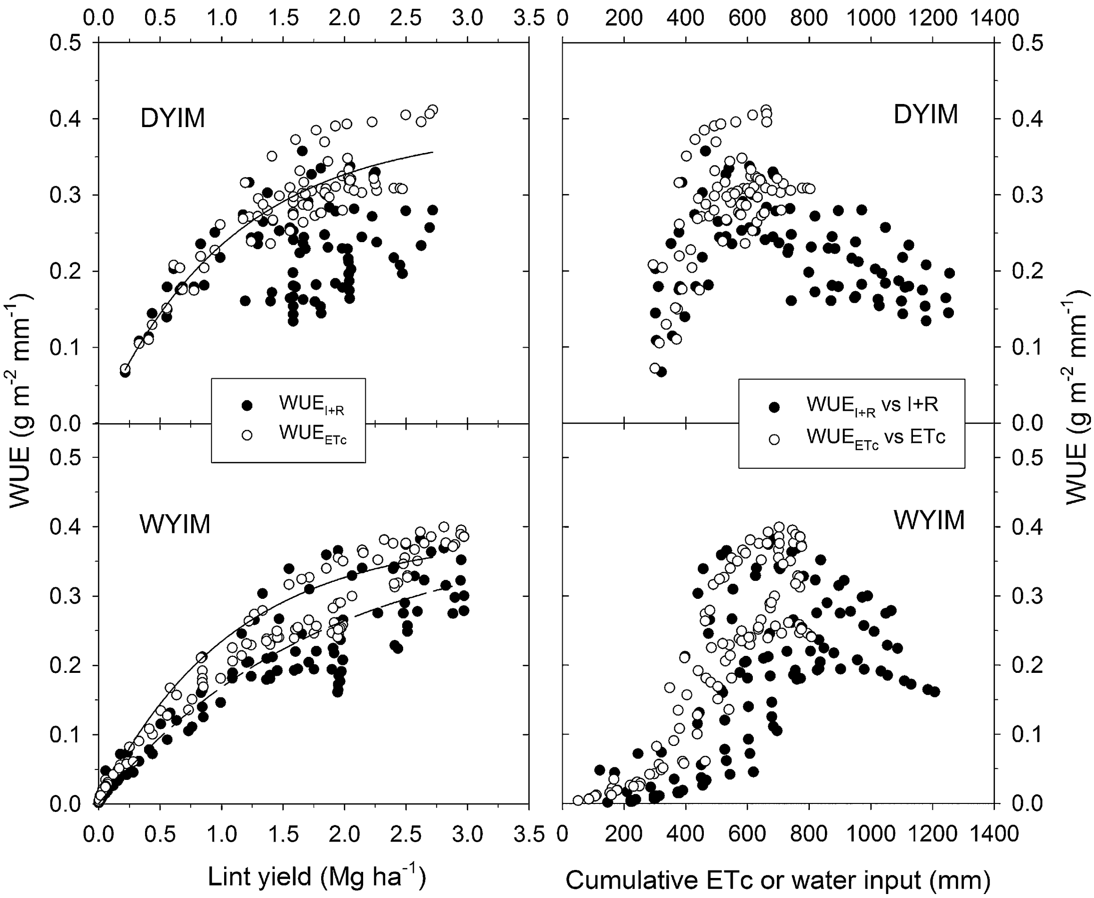

Fig. 8. Water use efficiency, WUE, in relation to cotton lint yield, Y, (left) and WUE in relation to cumulative crop evapotranspiration, ETc, and water input or irrigation, I, + rainfall, R, (right) simulated with dry year-based irrigation management (DYIM) and wet year-based irrigation management (WYIM). Data points (n = 72) include the two extreme (dry and wet) years from each of 20-year (1987–2006 and 1988–2007) simulations for six farm fields at six different irrigation regimes. $WUE_{I+R} = Y/(I + R)$ and $WUE_{ETc} = Y/ETc$. The fit curve equations are $WUE_{ETc} = 0.39(1 - \exp(-0.93Y))$, $R^2 = 0.79$ for the DYIM and $WUE_{ETc} = 0.47(1 - \exp(-0.53Y))$, $R^2 = 0.95$ and $WUE_{I+R} = 0.39(1 - \exp(-0.56Y))$, $R^2 = 0.85$ for the WYIM.

a scope of this study. While there are some specified models to deal with the issues, the same limitation to EPIC is found on most crop models including DSSAT (Hoogenboom et al., 2004) and RZWQM (Ma et al., 2006) which are widely used for crop simulation. As it is mentioned earlier in this section, EPIC is an adequate model to simulate long-term crop yield as well as complex rotations and fallow-cropping systems. Most of all, parameters of the model are well estimated under the Texas conditions as it was born in Texas. These make EPIC one of the best options for evaluating crop water management and alternative management scenarios in South Texas.

The relationships between yield and irrigation have been reported to be linear (Irmak et al., 2000) as well as curvilinear (Cetin and Bilgel, 2002; Yazar et al., 2002b). Meanwhile, our simulation study showed that the relationships between yield and water input (irrigation + rainfall) for both maize and cotton were curvilinear showing parabola-curve patterns. The relationships between yield and ETc for maize and cotton have been reported to be linear (Jalota et al., 2006; Oktem et al., 2003; Payero et al., 2006; Yazar et al., 2002a). In this study, the relationships for both maize and cotton were not absolutely linear (an exponential curve pattern up to a lower amount of ETc and a linear pattern after that). The results also showed that under the South Texas conditions, it appears that maize requires ~700 mm of water input and ~650 mm of ETc to achieve a maximum yield of 8.5 Mg ha^{-1} while cotton requires between 700 and 900 mm of water input and between 650 and 750 mm of ETc to achieve a maximum yield of 2.0–2.5 Mg ha^{-1}. The differences between water input and ETc can be attributed to water losses due to 97% irrigation system efficiency as well as deep percolation. The current results indicate that the model can be used as a pre-season or long-term decision tool for irrigation management of the crops. For example, one who operates a maize farm may make a pre-season and/or long-term decision to apply seasonal water input of 650 mm (93% of the maximum water input), making an allowance for 6% (0.5 Mg ha^{-1}) of yield reduction. We also showed the WUE relationships with crop yield, water input, and ETc (see Fig. 6 and 8). These relationships indicate that any water application above ~700 mm of water input or ~650 mm of ETc for maize, and 700–900 mm of water input or 650–750 mm of ETc for cotton would be not only surplus but also inefficient in crop water use and crop production. This information would be useful for policy makers and farm operators to aid their decisions when they make a guideline of water management for the crops based on WUE, crop water use, crop production, and the relationships between these.

While many studies focused on the evaluation of EPIC to simulate biomass and yield for various crops, some evaluated the model as a decision support tool in irrigation allocation and scheduling (Bryant et al., 1992, 1993; Cabelguenne et al., 1995, 1997; Santos et al., 2000). The on-farm simulation results in this study demonstrate that the EPIC model can be used as a decision support tool for crops under full and deficit irrigation conditions in South Texas. EPIC specifically appears to be effective in long-term and pre-season decision making for irrigation management of crops. While the current study presented a fundamental solution on water use and requirement as well as WUE of two crops, more studies are needed to employ the model as a decision support tool addressing other irrigation issues such as irrigation allocation and scheduling. Reference ET and phenologically based crop coefficients can be used for in-season irrigation management (Piccinni et al., 2007). Simulation models are also expected to be effective tools for in-season irrigation scheduling.

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